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Original Article

Effect of cement loss on stress distributions in class II inlays: a three-dimensional finite element analysis of resin tooth

Myoung-Uk Jin*

Department of Conservative Dentistry, School of Dentistry, Kyungpook National University, Daegu, Republic of Korea
Advanced Dental Device Development Institute, Kyungpook National University, Daegu, Republic of Korea

Purpose: The aim of this study was to evaluate, by means of 3D finite element analysis, the effect of marginal cement loss on the stress distribution of class II MOD inlays. **Materials and Methods:** The resin model teeth scanned with optical 3D digitizing system (Comet 5, Steinbichler optotechnik). The 3D images were processed by SolidWorks (Dassault Systèmes SolidWorks Corp., Concord). ANSYS workbench V13 (ANSYS Inc., Canonsburg) was used to mesh and analyze 3D FE model. Class II MOD inlay cavities were filled with Lava™ zirconia ceramic inlay (3M ESPE), IPS Empress II (Ivoclar Vivadent) and Tescera™ (Bisco). As for the resin cement, Variolink® II (Ivoclar vivadent) was used. After restoration, an oblique load of 400 N and a vertical load of 400 N were applied to the five areas. von Mises stress on the restorative materials, cement layer and bonding layer were evaluated separately. **Results:** Oblique loading generated higher von Mises stress than vertical loading. The intact cement layer showed lower stress distribution than both marginal and base cement loss models, with stress concentrated at the edges of the cement defects. Inlay materials with lower elastic modulus transmitted more stress to the cement layer. Under oblique loading, the composite resin inlay showed the highest stress, while in the base cement loss group, stress followed the order of material stiffness: zirconia > lithium disilicate > composite resin. **Conclusion:** Within the limitations of this study, it was concluded that areas with cement loss showed stress concentration, which could further lead to the destruction of the cement layer and consequently affect the longevity of the restoration. **(J Dent Rehabil Appl Sci 2025;41(2):119-31)**

Key words: finite element analysis (FEA); dental stress analysis; dental restoration; dental cements; inlays

Introduction

Growing interest in esthetic posterior restorations has stimulated interest in the development of new materials and techniques in dentistry.[1] Dental ceramics are the material of choice because of superior esthetics, biocompatibility, and resistance to masticatory forces.[2] For dental ceramic materials, the first requirement is ability to withstand the masticatory forces in the oral environment. However bulk fracture is a frequent cause of failure of ceramic inlays.[3,4] Therefore, elastic modulus is an important property as it affects the longevity of the dental restoration and the soundness of the surrounding dental tissue.[5] Efficient adhesion between cavity walls and restorative materials is important for long-lasting restorations.[6]

Resin cements are used to retain indirect restorations and to promote an adequate seal between restoration and tooth substrates. Cement loss within

*Correspondence to: Myoung-Uk Jin
Professor, Department of Conservative Dentistry, School of Dentistry, Advanced Dental Device Development Institute, Kyungpook National University, 2177 Dalgubuldaero, Jung-gu, Daegu, 41940, Republic of Korea
Tel: +82-53-600-7623, Fax: +82-53-426-8958, E-mail: musljin@knu.ac.kr
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the luting gap of bonded inlays is considered a major problem with bonded inlays. Loss of luting resin cement can result in plaque accumulation, marginal staining, postoperative hypersensitivities, recurrent caries and consequently complete loss of the restoration.[7] Deep marginal ditching of the luting gap could cause marginal fractures of inlay materials because of insufficient support for the marginal areas of brittle materials, like enamel or ceramics.[8]

Clinically, quantitative analysis of cement loss is difficult to perform. Therefore, finite element analysis (FEA) is an effective method to evaluate the biomechanical characteristics of dental restorative materials, able to reveal the inaccessible stress distribution of restorations and tooth structures. For this reason, finite element analysis has been widely employed to investigate the impact and effect on stress distributions.[9]

The aim of this study was to evaluate, by means of 3D finite element analysis, the effect of marginal and base cement loss on the stress distributions of three different kinds of inlay materials, cement layers and bonding layers. The null hypothesis of this study was that the presence or absence of marginal and base cement loss would not significantly affect the stress distributions within the inlay materials, cement layers, and bonding layers.

Materials and Methods

Finite element modelling

The study was performed using a three-dimensional finite element analysis. A resin model tooth was scanned with optical 3D digitizing system (Comet 5, Steinbichler optotechnik, Neubeuern, Germany).[10] Image processing software (SolidWorks, Dassault Systèmes SolidWorks Corp., Concord, USA) was employed to make the boundaries of enamel, dentin and pulp. The mesh structure of the solid 3D model was created using the FEA software (ANSYS workbench V13, ANSYS Inc., Canonsburg, USA).

The global coordinate system of the resin tooth was defined as follows: the occlusocervical direction was regarded as the X-axis, the mesiodistal direction as the Y-axis and the buccolingual direction as the Z-axis. Liner, four-noded tetrahedral elements were used in the mesh of the 3D volume element shape.

In this study, three types of FEA models were constructed (Fig. 1). First, an intact cement layer model consisted of 221,193 elements and 371,079 nodes. Second, the marginal cement loss model consisted of 241,021 elements and 411,378 nodes. Third, a base cement loss model consisted of 214,266 elements and 359,384 nodes. The 3D meshed mandibular left

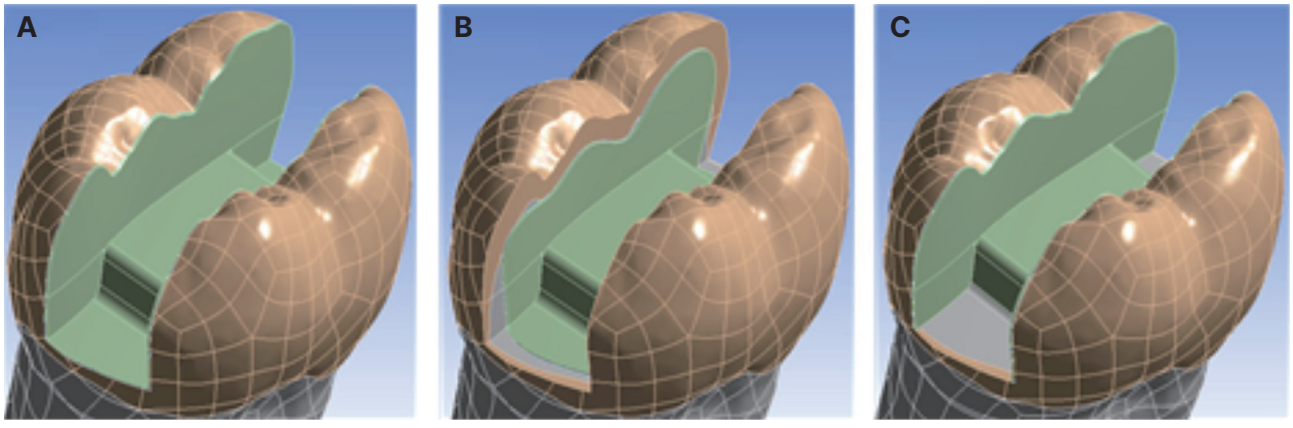

Fig. 1. (A) Group 1 with the intact cement layer. (B) Group 2 with the marginal cement loss. (C) Group 3 with the base cement loss.

first molar with MOD inlay cavity is shown in Fig. 2. A 3-D class II MOD inlay design was created with 3.5 mm occlusal width and 3 mm cavity depth. The cavity design was characterized by flat floor and rounded internal line angles. No bevels were added to any margin of the preparations. A resin cement (Variolink® II, Ivoclar Vivadent, Schaan, Liechtenstein) of 70 μm and a bonding layer of 10 μm was created to cover the entire cavity surface,[11] as shown in Fig. 2.

The elastic modulus and Poisson's ratio of the materials used are shown in Table 1.[5,12-18] All materials were assumed to be linearly elastic, homogeneous and isotropic.[19] In these models, the outer surface of the root under CEJ 2 mm was fixed to prevent rigid body motion for finite element analysis.

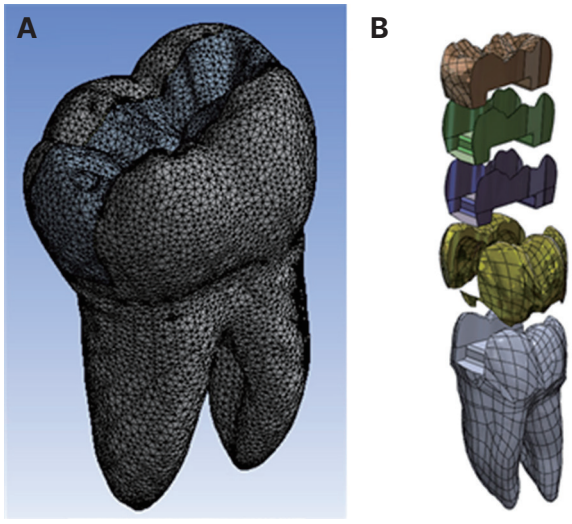

Fig. 2. (A) FEA model used in this study. (B) inlay, 70 μm cement layer, 10 μm bonding layer, enamel, dentin (from top to bottom).

Restorative materials

Two all ceramic materials and one indirect composite resin were selected for investigation: Lava™ (3M ESPE, St. Paul, USA), IPS Empress II (Ivoclar Vivadent) and Tescera™ (Bisco, Schaumberg, USA). As for the resin cement, Variolink® II (Ivoclar vivadent) was used.

Experimental groups

The current study evaluated the three types of FEA models (Fig. 1).

Group 1 - intact cement layer (control)

Group 2 - marginal cement loss

Group 3 - base cement loss

Loading conditions

A vertical load of 400 N was applied to the central fossa, distal marginal ridge, mesial marginal ridge, mesiobuccal cusp tip and distobuccal cusp tip.[10] An oblique load of 400 N was applied to the central fossa, distal marginal ridge, mesial marginal ridge, palatal inclination of mesiobuccal cusp and distobuccal cusp (Fig. 3).[20]

Table 1. Mechanical properties of the resin tooth and the materials used in the study

	Elastic modulus (GPa)	Poisson's ratio	References
Enamel	84.1	0.30	12 & 13
Dentin	18.6	0.31	14 & 15
Adhesive	4.5	0.30	11 & 16
Variolink® II	8.3	0.35	17
IPS empress2	102	0.3	5
Lava™	210	0.23	5
Tescera™	9.1	0.30	18

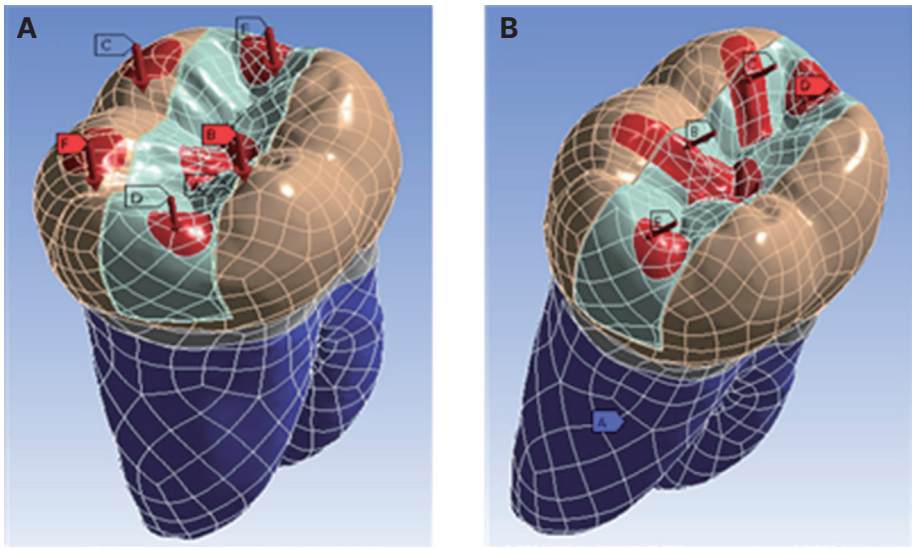

Fig. 3. Loading conditions. (A) a vertical loading of 400 N. (B) an oblique loading of 400 N.

Stress analysis

For both inlay materials and loading conditions, 3D finite element analysis was used to evaluate the von Mises stress on the restorative materials, cement layers and bonding layers. The statistical method used in this study was Stochastic Finite Element Method (Stochastic FEM), which integrates uncertainties in material properties, loading conditions, and geometry into a probabilistic model. This approach enhances the reliability of the analysis and predicts the probabilistic behavior of complex systems.

Results

The von Mises stress distribution was analyzed as follows.

To analyze stress distribution and location, all the created structures were isolated from the rest of the model. The von Mises stress on the restorative materials, cement layer and bonding layer were evaluated separately.

Generally, oblique loads applied at 35-degree angle to long axis of resin tooth generate more von Mises stress than loads directed along the long axis of the tooth. For the cement and bonding layers, the intact cement layer (Group 1) showed lower stress than the cement layers of margin and base loss (Group 2 and Group 3). The highest stress values for all marginal cement loss and base cement loss models were concentrated on the edge of the cement and bonding layers.

Comparison of stress distributions between Group 1 and 2 revealed distinct patterns across the enamel, inlay, cement, and bonding layers. In the enamel, von Mises stress decreased in the marginal cement loss model (Group 2) under both vertical and 35-degree oblique loading conditions, although the difference between Group 1 and 2 was not statistically significant (Fig. 4). In the inlay materials, stress behavior varied depending on the loading direction. Specifically, von Mises stress increased in Group 2 under vertical loading (Fig. 5), while it decreased under 35-degree oblique loading (Fig. 6). For the cement and bonding layers, von Mises stress values increased under both loading conditions in Group 2, with stress concentrated at the edges of these layers as shown in Fig. 7 to 10.

Notably, the composite resin inlay (Tescera™, Bisco) exhibited the highest von Mises stress under oblique loading (Fig. 4). Comparison of stress distributions between Group 1 and Group 3 revealed material-dependent variations across different layers. In the enamel layer, there were no noticeable differ-

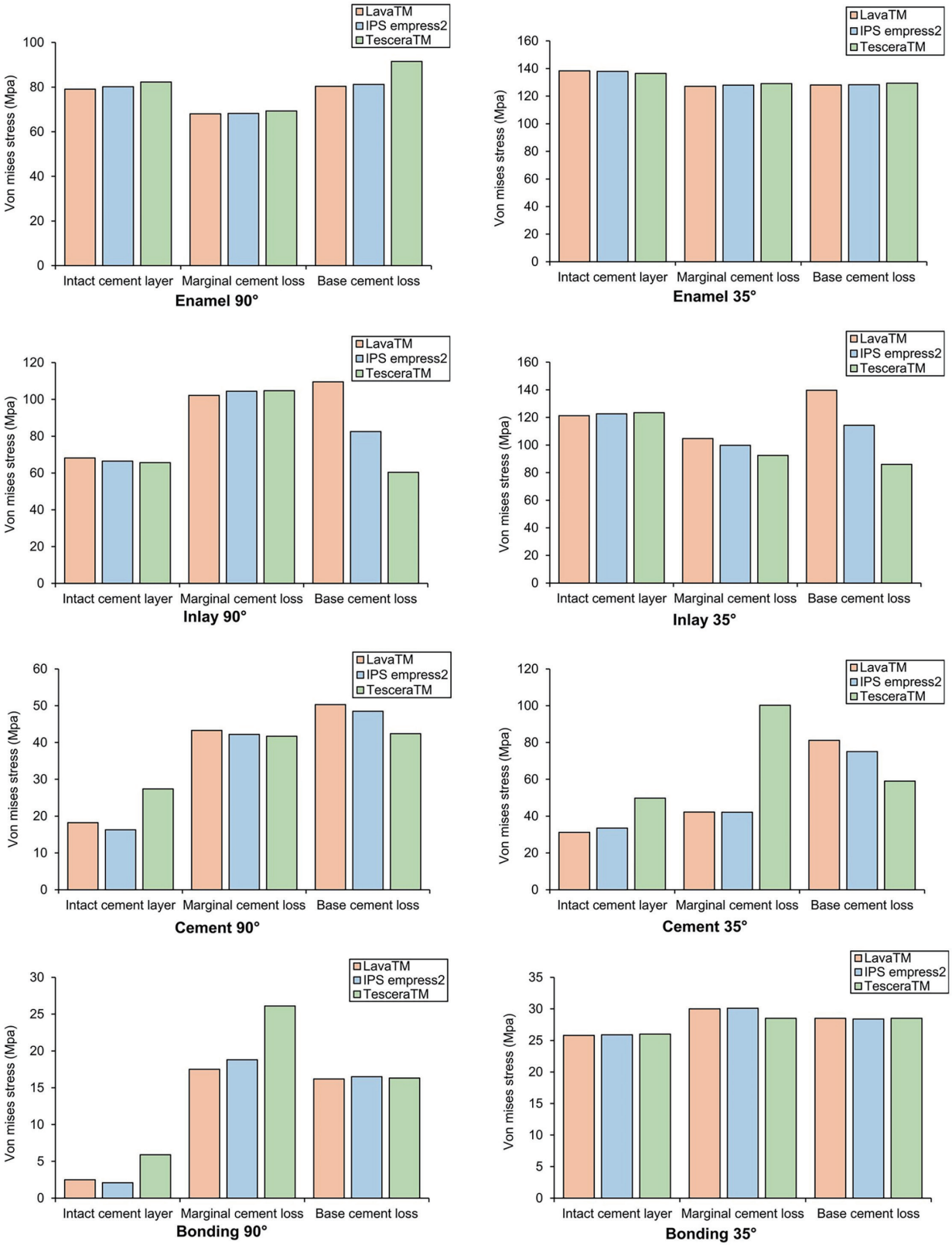

Fig. 4. Von Mises stress (MPa) distribution in the enamel, inlay, cement, and bonding layers under vertical (90°) and oblique (35°) loading conditions: The analysis was performed using Stochastic FEM to incorporate uncertainties in material properties, loading conditions, and geometry.

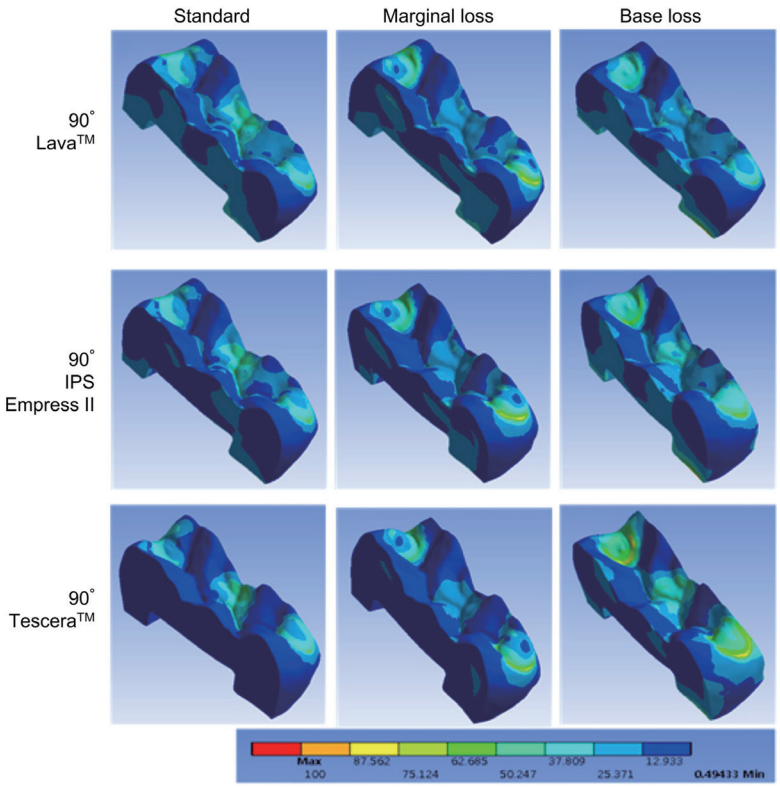

Fig. 5. von Mises stress distribution of inlays, when vertical load was applied.

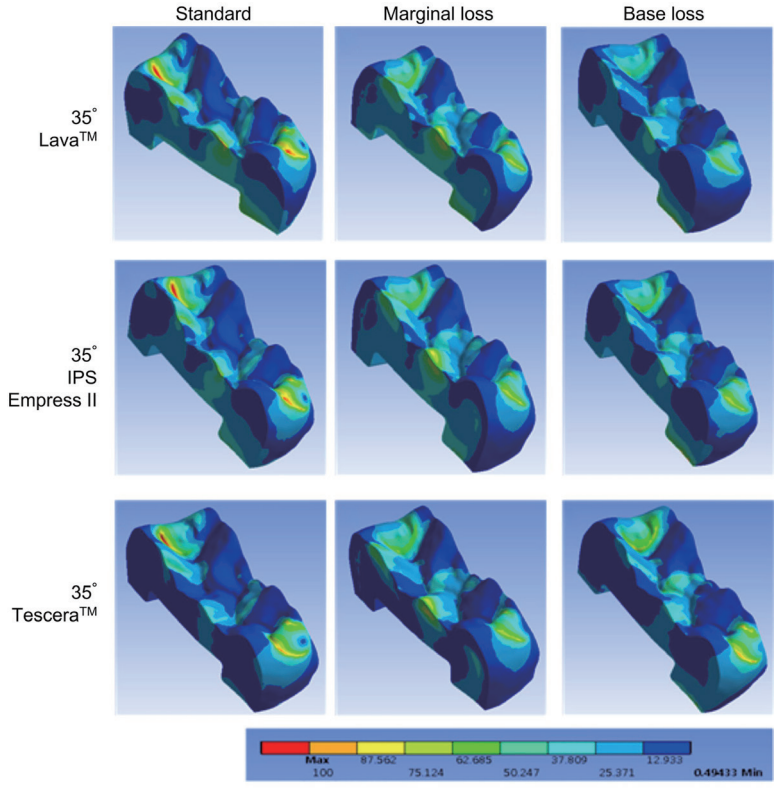

Fig. 6. von Mises stress distribution of inlays when 35-degree oblique load was applied.

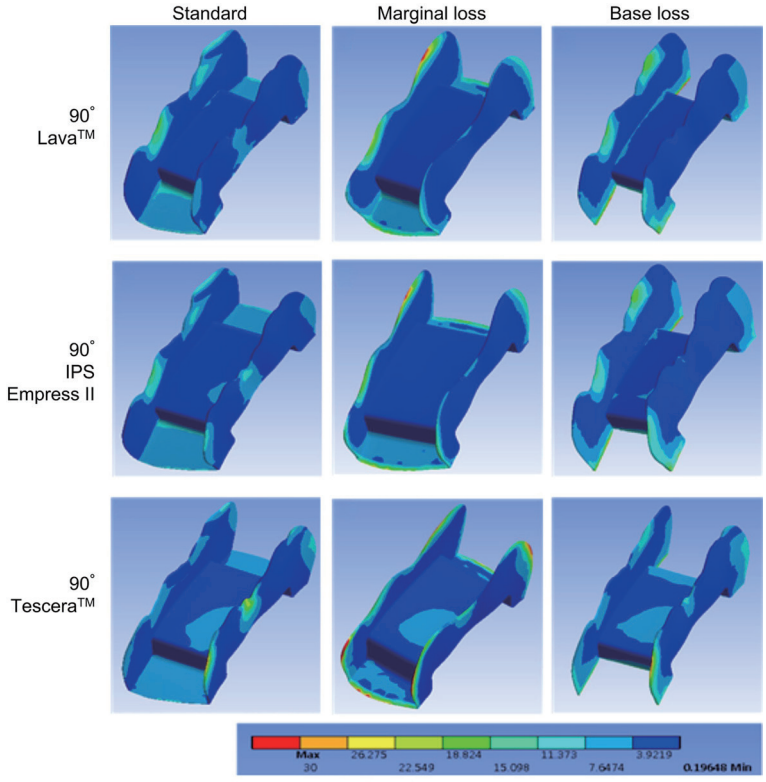

Fig. 7. von Mises stress distribution of cement layers, when a vertical load was applied.

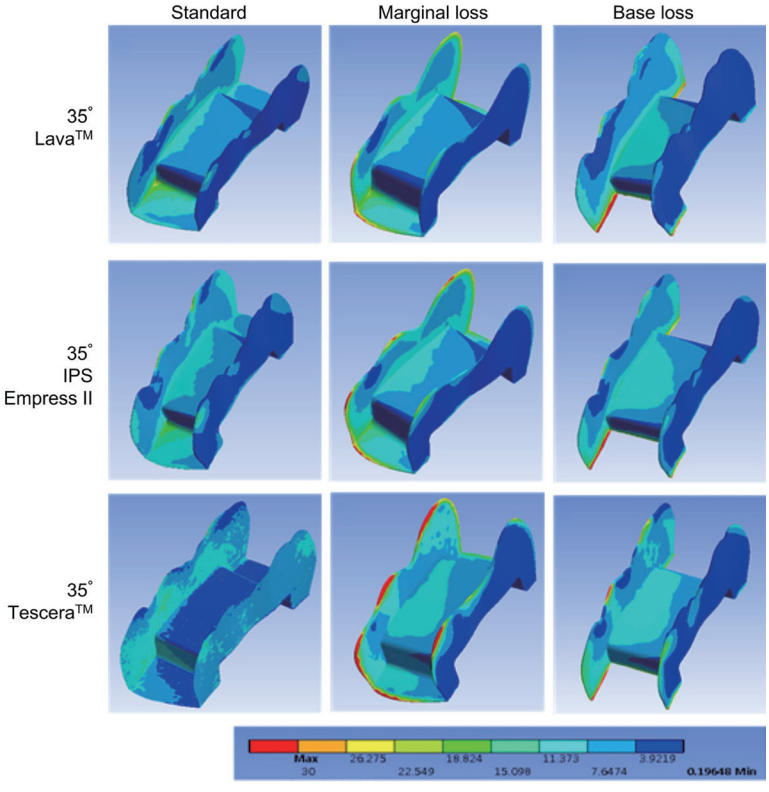

Fig. 8. von Mises stress distribution of cement layers, when 35-degree oblique load was applied.

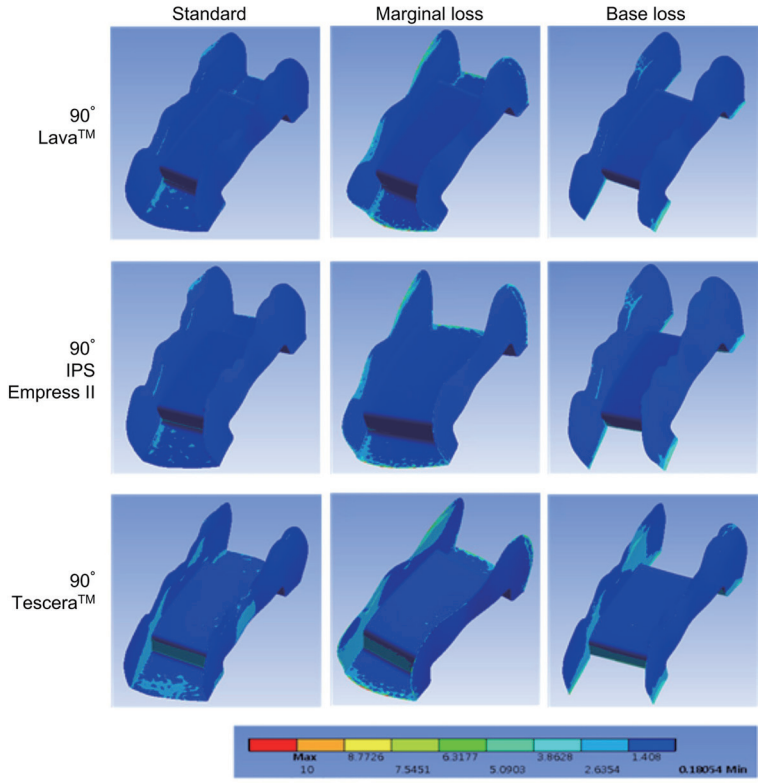

Fig. 9. von Mises stress distribution of bonding layers, when a vertical load was applied.

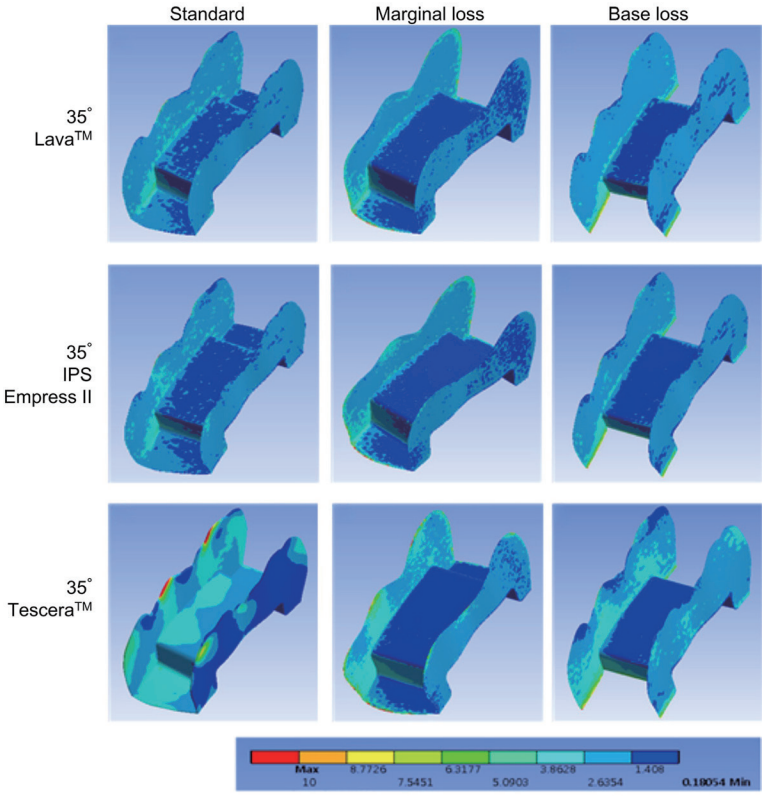

Fig. 10. von Mises stress distribution of bonding layers, when 35-degree oblique load was applied.

ences in von Mises stress between the two groups (Fig. 4). However, in the inlay materials, the Zirconia inlay (Lava™, 3M ESPE) showed the highest von Mises stress, followed by the lithium disilicate inlay (IPS Empress II, Ivoclar Vivadent) and the composite resin inlay (Tescera™, Bisco), reflecting the descending order of elastic modulus among the materials (Fig. 4). In the cement and bonding layers, von Mises stress increased under vertical loading and further increased under 35-degree oblique loading, indicating a higher stress concentration with angled forces.

Discussion

Inlay restorations have become treatment options to make the residual tooth structure strong and resilient. To restore the posterior teeth aesthetically, composite resins and dental ceramics are the material of choice.[21] Up to recently, controversial results have been obtained from many investigations of the effects of restorative materials on stress distributions in restorations and tooth structures.[5] However, there were few studies in the literature evaluating the association of cement loss and stress distribution of inlay materials. Three-dimensional quantitative measuring of cement loss in vivo is difficult to perform. For better understanding of this issue, a 3D finite element analysis of stresses associated with the inlay materials and cement loss in mandibular molar was performed in this study.

In the present study, cement loss did not affect the stress value of enamel layers. However, the stress distribution was changed as cement loss occurred. Therefore, the null hypothesis of this study was rejected. In group 2 (marginal cement loss) and 3 (base cement loss), when vertical and oblique loads were applied, the von Mises stress values of three inlay materials showed significant differences compared with group 1 (control). In group 2, when 400 N oblique load was applied, the von Mises stress values of inlays were lower than group 1 as shown in Fig. 6 and 4D. This was because that the cement loss space allowed the inlay materials to deform instead of increasing the stress. In contrast, when 400 N vertical load was applied, the von Mises stress was higher than group 1 (Fig. 5 and 4C). This could be explained by the speculation that the cement loss space could not absorb the stress and stress concentration occurred in the inlay materials itself. In group 3, decreasing order of von Mises stress for inlay materials was as follows: Lava™ > IPS Empress II > Tescera™.[5] This decreasing order is same as the decreasing order of elastic modulus. Therefore, the elastic modulus of inlay materials may have an influence on the stress distribution.

For the cement and bonding layers, von Mises stress of cement and bonding layers showed significantly lower stress value than inlay materials. Inlay materials absorbed the stress and transferred the part of stress to the cement and bonding layers. In the present study, cement layer was subject to about 20 - 70 Mpa of von Mises stress (Fig. 4E and 4F). The ultimate tensile strength of resin cement was 45.1 Mpa and the ultimate compressive strength of resin cement was 178 Mpa.[17] The occlusal forces near or over the value of ultimate tensile and compressive strength could result in more stress concentration and more destructive cement loss consequently. Regardless of type of inlay materials, loading condition, and partial cement loss, von Mises stress of group 2 and 3 showed higher value than group 1. As shown in the Fig. 7 to 10, stress concentration occurred at the edge of cement loss area. This indicates that the cement loss area allowed inlay deformation and line angle, where inlay and cement layer met, arresting the inlay from deformation therefore the stress concentration occurred.

In contrast to the results of this study, Ausiello et al. showed that ceramic inlays transferred more stresses to the resin cement and adhesive layers than indirect composite resin inlays. Indirect composite resin inlays showed better results in terms of stress distributions.[9] Similarly, Boschian Pest et al. suggested that if restorative materials were more rigid, they would be more stress-resistant. However rigid restorative materials transferred most of the functional stress to tooth substrate and hence increased the risk of tooth fracture.[22] Similar to the result of this study, Mesquita et al. indicated that composite resin could

not absorb functional stress. As a result, functional stress would be transmitted to the tooth substrate and tooth structure could suffer from a destructive effect.[23]

The bond strength between tooth substrates and restoration materials is another important contributing factor to a successful restorations1.[24,25] Functional stress applied to the restorative materials may cause failures in the resin cements. Dejak and Milotkosski reported that failures in the resin cements might be influenced by the restorative materials.[17] Sorensen and Munksgaard suggested that without the adhesive, the failure rate of inlays cemented with dual-cure resin cement was significantly higher.[26] The evaluation of the interfacial area between the tooth structure and inlay margin has always represented a pivotal tool in vitro and in vivo experiments. Up to now, there were no standards for the acceptance of dental materials on the wear of resin-based luting cements.[27] Therefore, the amount of cement loss was determined arbitrarily. In the case of base cement loss, the worst scenario of cement loss was assumed when indirect restoration was not well cemented to the gingival wall.

Posterior teeth are subject to functional and parafunctional forces of varying magnitudes and directions.[11] An oblique and vertical loads of 400 N were applied in the present study, which was probably lower than could be applied by mastications in vivo. According to Tortopidis, in posterior areas, the maximum bite force was 580 N.[28] Other studies evaluated that the occlusal forces of males (552 N) and females (441 N) were different.[11] Most of the studies clearly showed that oblique loads generate more stress than loads directed along the long axis of the tooth. In the current study, an oblique and vertical loads of 400 N was applied to the central fossa, distal marginal ridge, mesial marginal ridge, lingual inclination of mesiobuccal cusp and distobuccal cusp. The loads corresponded to the forces acting on the mandibular molar during centric occlusion and the mastication.

The results of FEA study should be interpreted with a caution. In the finite element model, all the materials used in this study was assumed to be linearly elastic, homogeneous, and isotropic. An oblique and vertical loads applied in this study did not reflect the actual functional forces encountered intraorally. Also the entire oral environment could not be included in this study model, therefore simplifications and assumptions were used.

Further experimental validation of the FEA study is needed to assess the result of this study.

Conclusion

This study demonstrated that when cement loss occurs, stress is concentrated at the edge of the loss area. Such stress concentration may exacerbate the degradation of the cement layer and negatively affect the longevity of the restoration. Therefore, in clinical practice, it is essential to apply precise adhesive techniques and ensure the integrity of the initial cementation to maintain the stability of the restoration.

From a clinical perspective, these findings highlight the critical role of cement continuity in the long-term success of Class II inlay restorations. Particularly, the stress concentrations identified through finite element analysis in regions of cement loss suggest that even minor imperfections during cementation could initiate mechanical failure over time. This underscores the necessity for clinicians to adopt meticulous cementation protocols, especially in areas susceptible to masticatory forces.

ORCID

Myoung-Uk Jin https://orcid.org/0000-0001-9263-047X

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2급 인레이의 경계부 시멘트 소실로 인한 레진 치아의 응력분포에 관한 유한요소 분석

진명욱* 교수

경북대학교 치과대학 치과보존학교실

경북대학교 첨단치과의료기기개발연구소

목적: 본 연구는 3차원 유한요소분석법적 연구를 통해 치아와 2급 간접 수복물 사이의 시멘트 계면의 소실이 있을 때의 응력분포를 평가하는 것이다.

연구 재료 및 방법: 레진 치아 모델을 광학 3차원 디지털 스캐너(Comet 5, Steinbichler Optotechnik)로 스캔하였다. 획득된 3차원 이미지는 SolidWorks (Dassault Systèmes SolidWorks Corp., Concord)를 이용하여 처리하였으며, ANSYS Workbench V13 (ANSYS Inc., Canonsburg)을 사용하여 3차원 유한요소 모델을 분석하였다. Class II MOD 인레이 수복은 Lava™ 지르코니아 세라믹 인레이(3M ESPE), IPS Empress II(Ivoclar Vivadent), 그리고 Tescera™ (Bisco)를 이용하여 진행되었다. 레진 시멘트는 Variolink® II (Ivoclar Vivadent)를 사용하였다. 수복 후에는 5개의 부위에 각각 400 N의 사선 하중과 수직 하중을 가하였다. 수복 재료, 시멘트층, 접착층에 발생한 von Mises 응력을 각각 평가하였다.

결과: 사선 하중은 수직 하중보다 더 높은 von Mises 응력을 발생시켰다. 손상되지 않은 시멘트 층은 변연 시멘트 손실 모델과 기저부 손실 모델보다 응력 분포가 낮았으며, 응력은 시멘트 결함 가장자리에 집중되었다. 탄성 계수가 낮은 인레이 재료일수록 시멘트 층에 더 많은 응력이 전달되었다. 사선 하중에서 복합 레진 인레이는 가장 높은 응력을 나타냈지만, 기저부 시멘트 손실에서는 재료의 강성 순으로 응력이 발생하였다: 지르코니아 > 리튬 디실리케이트 > 복합 레진

결론: 본 실험의 결과에 의하면 시멘트 소실이 있는 경우 소실부위에 응력의 집중이 나타나며, 이는 시멘트층의 파괴를 더욱 심화시켜 수복물의 수명에 영향을 미칠 수 있다.

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주요어: 유한요소분석(FEA); 치과 응력 분석; 치과 수복물; 치과용 시멘트; 인레이

*교신저자: 진명욱

(41940)대구광역시 중구 달구벌대로 2177 경북대학교 치과대학 치과보존학교실

Tel: 053-600-7623 | Fax: 053-426-8958 | E-mail: musljin@knu.ac.kr

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